**Problem Statement:** Given a sequence of aligned images, such as those used to compose panoramas, recover the response curve, varying exposures, and vignetting. Correct for the effects of variable exposure and vignetting in the given images.

Panoramic photograph sequence from Apollo 11, aligned using AutoStitch and composited without blending:

After compensation for spatiotemporal exposure variation -- vignetting and exposure duration -- and Photomontage blending:

**Sources of Vignetting**

- **Natural Vignetting:** \( \cos^4(\theta) \)
- **Optical Vignetting:** occlusion after aperture
- **Mechanical Vignetting:** occlusion before aperture

**Model and Approach**

\[
P_{x,i} = R\beta(t_iL_xM\alpha(r_{x,i}))
\]

\(x\) indexes over scene points
\(i\) indexes over images
\(P_{x,i}\) color of point \(x\) as seen in image \(i\)
\(R\beta\) response curve parameterized by \(\beta\)
\(t_i\) exposure of image \(i\)
\(L_x\) radiance toward camera of point \(x\)
\(M\alpha\) vignette curve parameterized by \(\alpha\)
\(r_{x,i}\) distance of point \(x\) from center of image \(i\)

**Recovery Ambiguities**

Exposure and scene radiance can only be recovered up to a scale ambiguity.

An additional exponential ambiguity exists for unknown response:

\[
R'(E) = R(E^{1/\gamma})
\]
\(t' = t^{\gamma}
\]
\(L' = L^{\gamma}
\]
\(M' = M^{\gamma}
\]
\(R'(t'L'M') = R(tLM)
\]

Givens: \(P_{x,i}, r_{x,i}\)

Unknowns: \(\alpha, \beta, L_x, t_i\)

Reconstruction error minimized using nonlinear optimization: alternating Nelder-Mead downhill simplex

**Compensation and Blending**

Exposure and vignette compensation only:

[Compensation and blending:](image)

[Photomontage blending (Agrawala et al. 2004):](image)